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Light Guide Layer Thickness Optimization for Enhancement of the Light Extraction Efficiency of Ultraviolet Light-Emitting Diodes

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Abstract

Consider material machinability and lattice mismatch sapphire as substrates for the ultraviolet-C light-emitting diodes (UV-C LEDs) are commonly used, but their high refractive index can result in the total internal reflection (TIR) of light whereby some light is absorbed, therefore caused reducing light extraction efficiency (LEE). In this study, we propose a method to optimize the thickness of a sapphire substrate light guide layer through first-order optical design which used the optical simulation software Ansys SPEOS to simulate and evaluate the light extraction efficiency. AlGaIn UV-C LEDs wafers with a light guide layer thickness of 150–700 μm were used. The simulation proceeded under a center wavelength of 275 nm to determine the optimal thickness design of the light guide layer. Finally, the experimental results demonstrated that the initial light guide layer thickness of 150 μm the reference output power of 13.53 mW, and an increased thickness of 600 μm resulted in output power of 20.58 mW. The LEE can be increased by 1.52 times through light guide layer thickness optimization. We propose a method to optimize the thickness of a sapphire substrate light guide layer through first-order optical design. AlGaIn UV-C LEDs wafers with a light guide layer thickness of 150–700 μm were used. Finally, the experimental results demonstrated that the LEE can be increased by 1.52 times through light guide layer thickness optimization.

Keywords: Deep-ultraviolet light-emitting diodes, Light extraction efficiency, Light guide layer, First-order optical design

Introduction

The COVID-19 pandemic has led to an increase in the global mortality rate. Although traditional ultraviolet (UV)-C mercury lamps can be sterilized, their mercury content, dispersed spectral wavelength, bulkiness, and short lifetime limits their applicability. UV-C light-emitting diodes (LEDs) are environmentally friendly, mercury free, and nonpolluting. The sterilization wavelength is concentrated between 260 and 280 nm. Because the light source is small and has a long lifetime, it has gradually replaced UV-C mercury lamps as the primary

sterilization light source. UV light destroys bacterial DNA or RNA structures and has been widely used to decontaminate surfaces, air, and water. The UV-C waveband between 260 and 280 nm has the greatest bactericidal effect, preventing the regeneration of microbial cells to achieve disinfection and sterilization [1–3]. Studies have documented the wide use of UV-C LEDs in medical phototherapy and in the disinfection and sterilization of water, food, and medicine for safe consumption [4–7]. Traditional mercury UV lamps are disadvantaged by their long warm-up times, short lifetime, risk of exploding, and environmental pollution; UV-C LEDs are superior in all aforementioned aspects [8–10]. The UV-C wavelength range is 100–280 nm, and the UV-C LED wavelength falls between 260 and 280 nm. Because the emission wavelength of LEDs is more concentrated, their

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sterilization efficiency and long-term reliability are also better than those of mercury UV lamps [11, 12]. However, the poor external quantum efficiency (EQE) and light extraction efficiency (LEE) of UV-C LEDs must be improved. The low EQE and LEE of AlGaIn-based UV-C LEDs are attributable to electron leakage and total internal reflection (TIR), which cause photons to be absorbed by the sapphire substrate and the materials in the p-GaN contact layer [13–15].

Approaches toward LEE improvement have involved using a nanopatterned sapphire substrate as a substrate for manufacturing UV-C LEDs. The growth of InGaIn-based LED mixed patterned sapphire substrates at the microscale and nanoscale was proposed by Wen Cheng Ke et al., who allowed the LED to embed nanoholes in the micropatterned sapphire substrate to improve its photoelectric characteristics [16]. Phillip Manley et al. employed a nanopatterned sapphire substrate in deep UV (DUV) LEDs, verifying the effects of such a nanopatterned structure on the LEE of sapphire [17].

Shao Hua Huang et al. employed wet-etching of a flip-chip structure to modify a sapphire substrate and give it bevel texture, improving the LEE of a nitride LED [18]. Dong Yeong Kim proposed an n-type GaN micromirror with an Al-coated slope barrier called a sidewall emission-enhanced DUV LED to improve the LEE of transverse magnetic polarization [19].

Some scholars have proposed changing the light path to improve LEE through the design of a secondary lens. For example, Renli Liang et al. used nanolens arrays to enhance the LEE of DUV LEDs through lithographic and wet-etching technology. Bin Xie et al. proposed a free-form lens with a brightness enhancement film to enhance the overall performance of a direct-illuminated LED backlight [20, 21]. UV-C LEDs and their characteristics related to organic material absorption influence the choice of packaging materials. Nagasawa and Hirano promoted the use of p-type butyl vinyl ether with a trifluoromethyl end structure on AlGaIn substrates as the encapsulated material to improve LEE [22]. Under long-term DUV irradiation, organic materials are subjected to severe molecular dissociation and destruction. To promote more efficient and reliable light extraction, a material with high resistance to UV light or inorganic materials is required. The airtightness of a package is also a key factor for evaluating packaging capability [23, 24]. To account for both high penetration and long-term reliability, quartz glass is often used as the packaging material for UV LEDs. When the cavity is hollow, high interface reflections reduce LEE; the cavity can be filled with liquid or organic glue with a low refractive index for LEE improvement. In this regard, Chieh-Yu Kang proposed a new type of DUV LED liquid packaging structure can achieve LEE improvements. Chien Chun Lu

demonstrated the higher and more reliable LEE of UV-C LEDs with a quartz-based hermetic package [25, 26].

Different packaging materials such as polydimethylsiloxane (PDMS) fluid doped with SiO₂ nanoparticles can improve the LEE of UV LEDs. Zhi Ting Ye proposed the nanoparticle-doped PDMS fluid enhanced the optical performance of AlGaIn-based DUV LEDs [27]. Yang Peng employed this encapsulation material doped with fluoropolymer on an aluminum nitride substrate to enhance the LEE of a chip-on-board encapsulation structure [28]. Joosun Yun and Hideki Hirayama proposed different wafer structures in a comparative study with six different flip-chip structures, obtaining an AlGaIn meta-surface for improved LEE [29].

It is also worth mentioning that photon management has been demonstrated as an efficient way to extract and harvest light and has been widely used in a variety of optoelectronic devices, including photodetectors and photoelectron chemical cells [30–33], solar cells [34, 35], and Micro-light-emitting diodes in display technology [36].

Research into the refinement of UV-C LEDs has yet to examine the effects of light guide layer thickness on LEE. When sapphire is used as the light guide layer material, the absorption rate is relatively low in the general blue wavelength band of 450 nm but relatively high in the UV-C LED 260–280 nm wavelength band, demonstrating the influence of thickness on LEE. Therefore, in this paper, an optimal value for the thickness of the light guide layer for the LEE of UV-C LEDs is proposed.

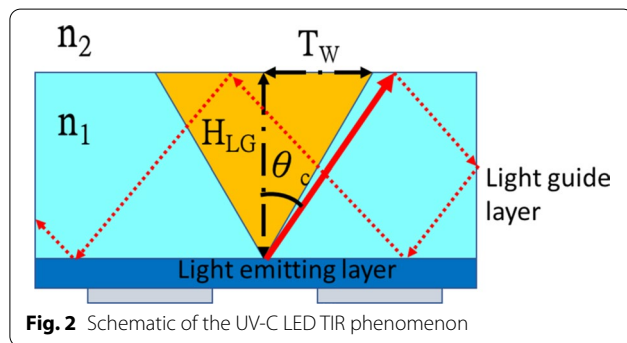
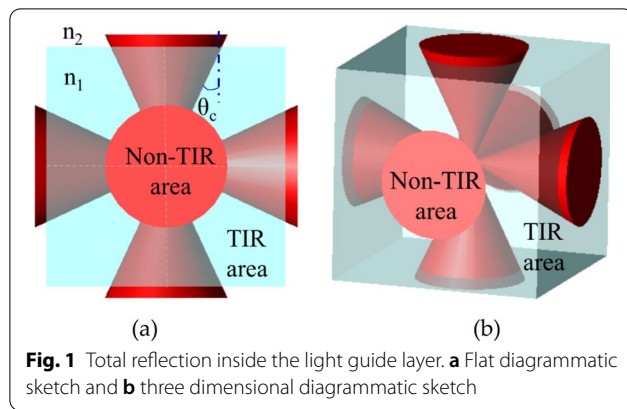
Methods

TIR Phenomenon in the Light Guide Layer

TIR is an optical phenomenon whereby the refractive index changes when light enters different media. When the incident angle is less than the critical angle, the light is divided into two parts; one part of the light is reflected and the other is refracted. Conversely, when the incident angle is greater than the critical angle, all light is internally reflected without refraction. The refractive index of the internal medium is n_1 , and the refractive index of the external medium is n_2 . The critical angle θ_c can be calculated using Eq. (1). When n_1 is 1.788, the critical angle θ_c of the TIR is 34.136°, as illustrated in Fig. 1. The red triangle cone represents the non-total reflection area that can penetrate the light guide layer and then exit it, and the remaining cyan area is the TIR area, wherein light bounces and is absorbed by the material, reducing the LEE.

$$\theta_c = \sin^{-1} \frac{n_2}{n_1} \quad (1)$$

When the length L and width W of the light guide layer are fixed, the thickness of the light guide layer H_{LG} affects



the TIR area. As depicted in Fig. 2, light exits from the light-emitting layer into the light guide layer and thus, the TIR phenomenon does not occur in the orange area. If the incident angle exceeds this area, TIR occurs in cyan area of Fig. 2. The width of this area can be defined as T_W , as expressed in Eq. (2).

$$T_W = \tan(\sin^{-1} \frac{n_2}{n_1}) \times H_{LG} \quad (2)$$

Simulation and Optimization of the Light Guide Layer Thickness to Enhance the LEE of UV-C LEDs

We used Solidwork 3D drawing software and Ansys SPEOS optical simulation software to construct the optical system and to simulate and optimize the effects of light guide layer thickness on LEE using first-order optical design. With Al_2O_3 acting as the light guide layer material, we modified the thickness to reduce absorption problems caused by TIR.

The wavelength of the UV-C LED chip was 275 nm, the length L 1.524 mm, and the width W was 1.524 mm, as presented in Fig. 3.

The light guide layer was composed of Al_2O_3 , the refractive index N_{LGL} was 1.782, and the light guide layer thickness (H_{LG}) interval was 150–700 μm . The light-emitting layer (LEL) had a thickness H_{LE} of 1.5 μm , the upper surface of the layer was a light-emitting surface, the lower surface was a partially absorbing and partially reflective layer, and the UV-C LED electrode thickness H_{pd} was 1.5 μm ; the material was set to partially absorb and partially reflect. Figure 3a illustrates the structure of the UV-C LED chip, and Fig. 3b is a simplified simulation diagram of the chip. The parameter settings are listed in Table 1.

Figure 4a presents a schematic of the UV-C LED three dimensional structure, and Fig. 4b is a schematic of the light trace of the simulated light-emitting surface.

This study analyzed the effects of light guide thickness from 150–700 μm on LEE; the simulated input radiant flux was 1 W, and the simulation result is presented in Fig. 5. When the thickness of the light guide was 150 μm , the relative radiant flux was 0.41 W, and when the thickness of the light guide was increased, the LEE increased in turn. At a 600- μm light guide thickness, the radiant flux was 0.62 W, a 1.512-fold increase. According to the simulation results, if the thickness is further increased, the LEE is close to saturation and does not increase.

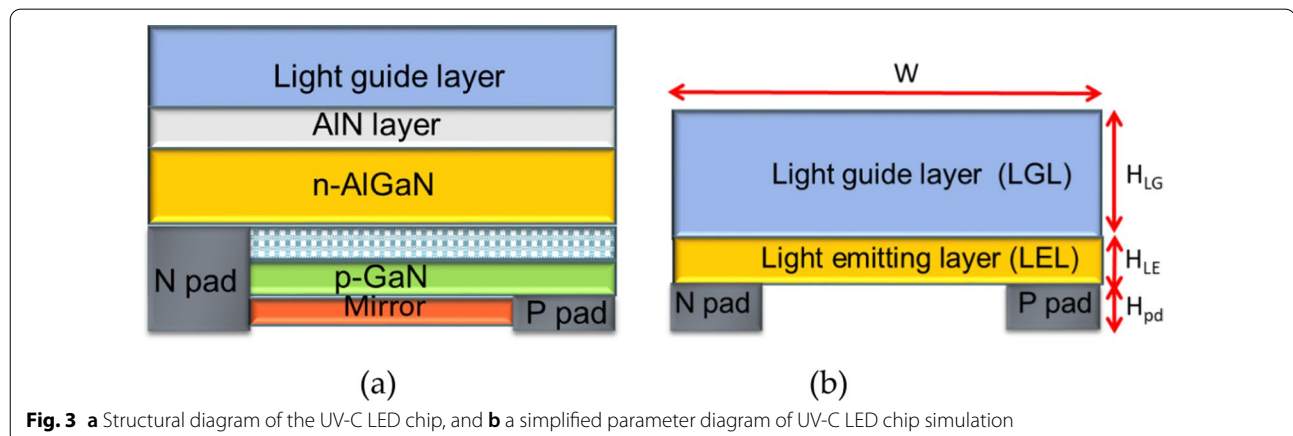


Table 1 UV-C LED chip simulation set parameters

Item	Characteristics	Value
Input power	Radiant flux	1 W
Wavelength	Polished	275 nm
Light guide layer (LGL)	Polished	Thickness: $H_{LG} = 150\text{ }\mu\text{m} - 700\text{ }\mu\text{m}$ Refractive index: $N_{LGL} = 1.782$,
Light emitting layer (LEL)	Polished	Thickness: $H_{LE} = 1.5\text{ }\mu\text{m}$ Refractive index: $N_{LEL} = 1.782$
P/N electrode layer	Cr/Au/Sn	Thickness: $H_{pd} = 1.5\text{ }\mu\text{m}$

When the thickness of the light guide layer was $700\text{ }\mu\text{m}$, the efficiency was only 2.2% higher than that of the layer at $600\text{ }\mu\text{m}$, as presented in Fig. 5.

Table 2 shows the relative radiant flux output and its magnification when the simulated radiant flux input was 1 W. The light guide layer with a thickness of $600\text{ }\mu\text{m}$ achieved the best LEE, magnification, and processing stability; however, at $700\text{ }\mu\text{m}$, it resulted in processing and cutting difficulties and a consequent decrease in yield.

We propose the light guide layer thickness optimization for enhancement of the LEE compared to the

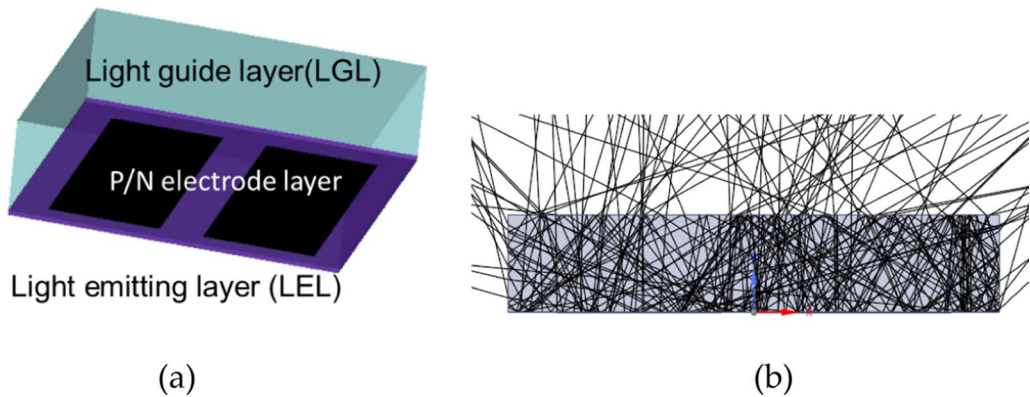


Fig. 4 Structure of the UV-C LED; **a** three dimensional structure of the UV-C LED simulation, and **b** light trace simulation diagram

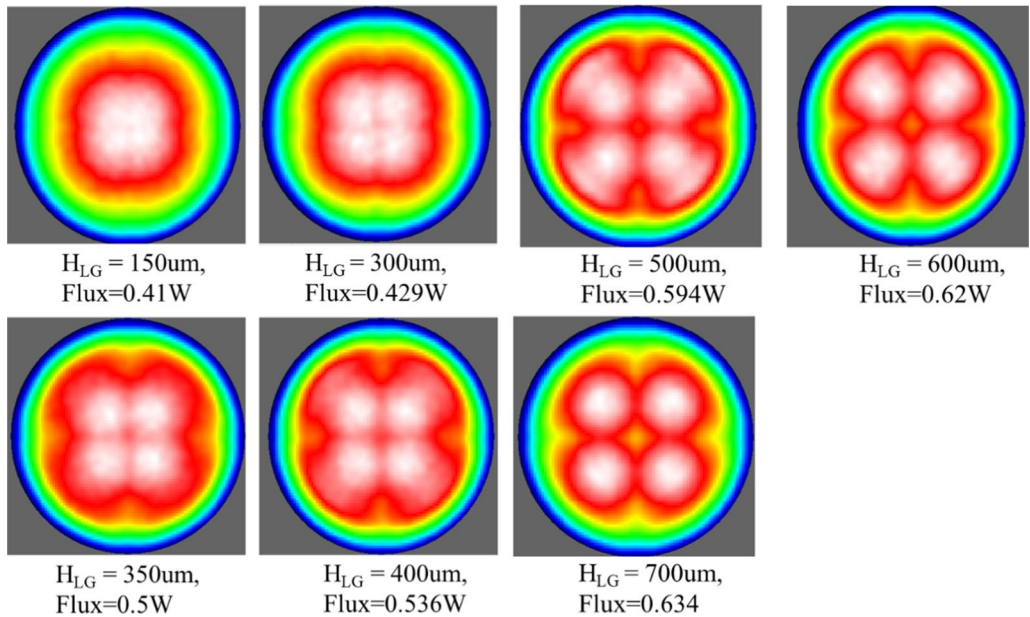
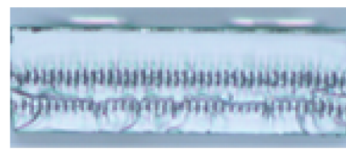
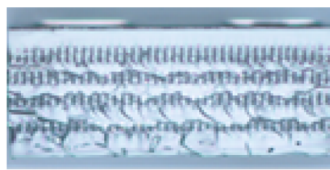
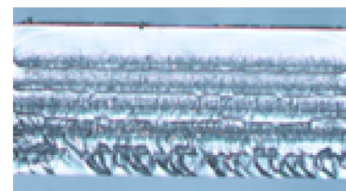
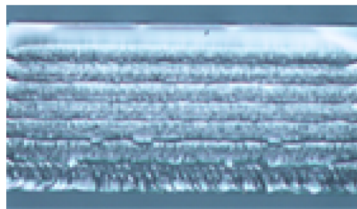
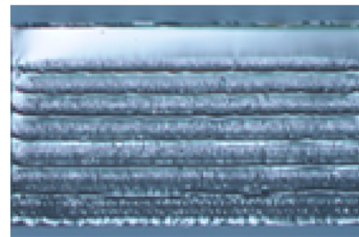
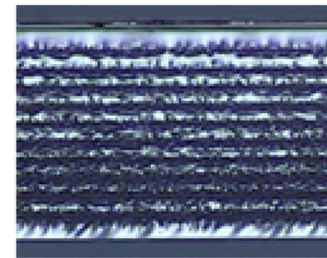


Fig. 5 LEE diagram of the simulated UV-C LED light guide with a thickness of $150 - 700\text{ }\mu\text{m}$

Table 2 LEE simulation results for a light guide layer thickness of 150–700 μm

thickness (μm)	Input radiation flux (Watt)	λ (nm)	(Relative radiant flux) mW	(Radiant flux magnification)
150	1	275	0.41	1
300			0.429	1.046
350			0.5	1.219
400			0.536	1.307
500			0.594	1.448
600			0.62	1.512
700			0.634	1.546

(a) $H_{LG} = 150 \mu\text{m}$ (b) $H_{LG} = 300 \mu\text{m}$ (c) $H_{LG} = 400 \mu\text{m}$ (d) $H_{LG} = 500 \mu\text{m}$ (e) $H_{LG} = 600 \mu\text{m}$ (f) $H_{LG} = 700 \mu\text{m}$ **Fig. 6** Side view of real UV-C LED samples with light guide layer thicknesses (H_{LG}) of **a** 150, **b** 300, **c** 400, **d** 500, **e** 600, and **f** 700 μm

nano-patterned sapphire substrate method, the advantages of the method do not need to go through the etching and embossing process.

Results and Discussion

Figure 6 illustrates the UV-C LED prototypes with different light guide layer thicknesses (H_{LG}). Figure 6a shows a H_{LG} value of 150 μm , the thickness parameter commonly used in industry settings that served as a reference measurement for this experiment. Figure 6e shows a H_{LG} of 600 μm , which is the optimal thickness for heightened LEE. In the industrial manufacturing process, increasing the thickness of the light guide layer will cause difficulty in cutting and lead to splitting problems. When the thickness of the light guide layer is 600 μm , it has reached the limit thickness of processing in the industry.

Table 3 lists the relative radiant flux of the different light guide layer thicknesses (H_{LG}). With H_{LG} of 600 μm , the radiant flux was 1.52 times higher than with

Table 3 LEE Results for light guide layer thicknesses of 150–700 μm

H_{LG} (μm)	Measured of Relative radiant flux		
	λ (nm)	Relative radiant flux (mW)	Radiant flux magnification
150	275	13.53	1
300	274	14.1	1.042
350	275	16.49	1.218
400	274	17.76	1.312
500	278	19.74	1.458
600	277	20.58	1.521
700	278	20.86	1.541

a thickness of 150 μm . Figure 7 illustrates the UV-C LED prototype simulation and measured LEE growth trend with different light guide layer thicknesses (150–700 μm);

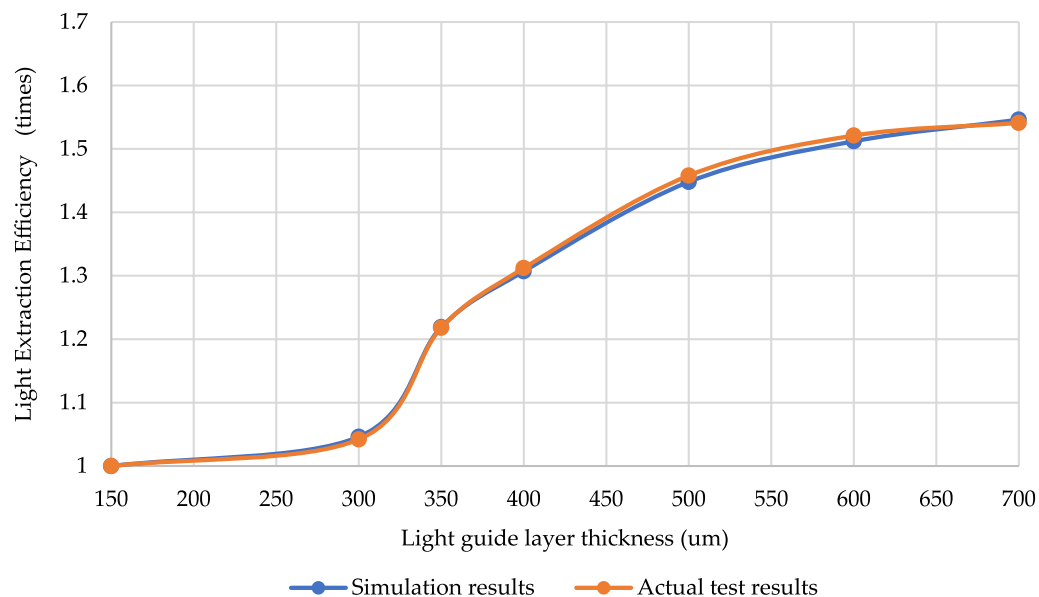


Fig. 7 Compared simulated and measured LEE enhance times of UV-C LEDs with a light guide layer thickness of 150–700 μm

Table 4 Difference between simulated and measured LEE of UV-C LEDs with light guide layer thicknesses of 150–700 μm

H_{LG} (μm)	Simulation results		Measured results	
	Relative radiant flux (mW)	Radiant flux magnification	Relative radiant flux (mW)	Radiant flux magnification
150	0.41	1	13.53	1
300	0.429	1.046	14.1	1.042
350	0.5	1.219	16.49	1.218
400	0.536	1.307	17.76	1.312
500	0.594	1.448	19.74	1.458
600	0.62	1.512	20.58	1.521
700	0.634	1.546	20.86	1.541

at H_{LG} of 700 μm, the growth rate was no longer obvious and had approached saturation. The simulation results are similar to those in the actual sample test.

Table 4 details the effects of the simulated UV-C LED on LEE under different light guide layer thicknesses; When the thickness of the light guide was 150 μm, the relative radiant flux was 13.53 mW, and when the thickness of the light guide was increased, the LEE increased in turn. At a 600-μm light guide thickness, the radiant flux was 20.58 mW, a 1.521-fold increase. Comparing the difference between simulation and measurement shows that the results are similar to those in the actual sample test.

Conclusions

This paper proposes a first-order optical design using Al_2O_3 material as the light guide layer to reduce the absorption caused by TIR and optimize the LEE of UV-C LEDs. The effects of light guide layers of different thicknesses on the LEE of UV-C LEDs were simulated and analyzed using SPEOS optical simulation software. Compared with the standard layer thickness of 150 μm, an optimized thickness of 600 μm resulted in a 1.52-fold increase in LEE. This improved UV-C LED LEE is beneficial for the use of such LEDs in sterilization systems and other future applications.

Abbreviations

DUV: Deep ultraviolet; H_{pd} : Electrode thickness; LEE: Light extraction efficiency; L: Length; LGL: Light guide layer; LE: Light emitting layer; TIR: Total internal reflection; UV-C LEDs: Ultraviolet-C light-emitting diodes; W: Width.

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Authors' contributions

Z.T. Ye, L.W. Hung and K.H. Hsu designed the experiments. C.Y. Heng analyzed data. Z.T. Ye and C.Y. Heng discussed the results and contributed to the writing of the manuscript. All authors read and approved the final manuscript.

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Available of data and materials

The datasets supporting the conclusions of this article are available in the article.

Declarations

Competing interests

The authors declare that they have no competing interests.

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